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On the close to threshold meson production in neutron–neutron collisions

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Abstract

A method of measuring the close to threshold meson production in neutron–neutron collisions is described where the momenta of the colliding neutrons can be determined with the accuracy obtainable for the proton–proton reaction. The technique is based on the double quasi-free $nn \to nnX^0$ reaction, where deuterons are used as a source of neutrons.

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In the last decade close to threshold production of mesons has attracted a lot of experimental and theoretical effort (see, for instance, [1,2]). Experiments performed at the accelerators CELSIUS [3–7], COSY [8–15], IUCF [16–19], SATURNE [20–25], and TRIUMF [26–31] delivered precise data on the pseudoscalar (π, η, η', K) and vector (ω, ϕ) meson production in proton–proton and proton–deuteron collisions. A secondary neutron beam with a spread in energy smaller than 1 MeV focussed onto liquid hydrogen targets ($\sim 10^{23}$ atoms/cm^2) permitted also precise investigations of the π meson production in the neutron–proton reactions [26,27,29].

Close to threshold meson production in proton–neutron collisions were also investigated by means of a technique based on a quasi-free scattering of the proton off the neutron bound in the deuteron. Thin windowless internal deuterium cluster targets ($\sim 10^{14}$ atoms/cm^2) make a detection of an undisturbed spectator proton and a precise determination of the reacting neutron momentum — and hence of the excess energy — possible.

Pioneering experiments of the π^0 meson creation in the proton–neutron reaction with the simultaneous tagging of the spectator proton resulted in a resolution

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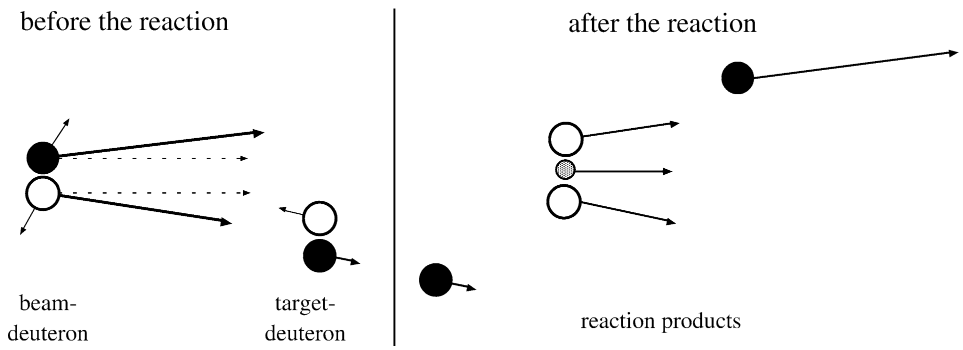

Fig. 1. Schematic depiction of the double quasi-free $nn \to nnX$ reaction. During the collisions of deuterons (left hand side of the figure, with the total momentum (solid arrow) resulting from the sum of the beam momentum (dotted arrow) plus the Fermi momentum (short arrow)) a double quasi-free neutron–neutron reaction may lead to the creation of mesons (small gray circle). The spectator protons (black circles) leave the reaction region with their initial momentum plus the Fermi momentum, which they possessed at the moment of the reaction. Neutrons are plotted as open circles. Due to the large relative momenta between spectators and the outgoing neutrons (~ 1 GeV$/c$ close to the threshold for the η meson production) a distortion of the nnX system by the accompanied protons can be neglected.

of the excess energy (σ) equal to $\sigma = 1.8$ MeV [32]. Similar studies including the production of heavier mesons will be continued at COSY [33,34].

Experimental investigations of the close to threshold production in neutron–neutron collisions, however, have not yet been carried out. A realisation of such studies — which are characterised by typical cross sections of $\leqslant$ μb — with high quality neutron beams bombarding a deuterium target is not feasible due to the low neutron beam intensities forcing to use liquid or solid deuterium targets which make the precise determination of the momentum of the spectator proton impossible. In this contribution a unique possibility of the precise measurement of the close to threshold meson production in neutron–neutron collisions is pointed out. The technique is based on the double quasi-free interaction of neutrons originating from colliding deuterons as depicted in Fig. 1. Utilizing this method, a precision of ~ 1 MeV can be obtained for determining the excess energy, since it depends only on the accuracy of the momentum or angle reconstruction for the registered spectator protons. At present cooled deuteron beams — available at the facilities CELSIUS, COSY, and IUCF — give the possibility of using this method for the studies of neutron–neutron scattering. Moreover, the usage of a stored beam circulating through an internal cluster target permits the study with high luminosities ($10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) in spite of very low target densities.

In the double quasi-free interaction, due to the small binding energy of the deuteron ($E_B = 2.2$ MeV), the colliding neutrons may be approximately treated as free particles in the sense that the matrix element for quasi-free meson production from bound neutrons is identical to that for the free $nn \to nnX$ reaction at the same excess energy available in the nnX system. The measurements at CELSIUS [5,6] and TRIUMF [30,31] have proven that the offshellness of the reacting neutron can be neglected and that the spectator proton influences the interaction only in terms of the associated Fermi motion [30].

The registration of both spectator protons will allow for a precise determination of the excess energy. A possible internal target facility based on the COSY-11 setup [35] is presented in Fig. 2. The energy and the emission angle of the "slow" spectator can be measured by an appropriately segmented silicon detector, whereas the momentum of the "fast" spectator proton can be analysed by the magnetic spectrometer. By means of the detection system shown in Fig. 2, a resolution of the excess energy of 2 MeV can be achieved for excess energies lower than 30 MeV as demonstrated in reference [34]. The double quasi-free $nn \to nnX^0$ reaction can be identified by the registration of both outgoing neutrons. For example, in order to measure the production of the η meson, a four meter distance for the time of flight measurement would be enough to obtain 8 MeV (FWHM) missing

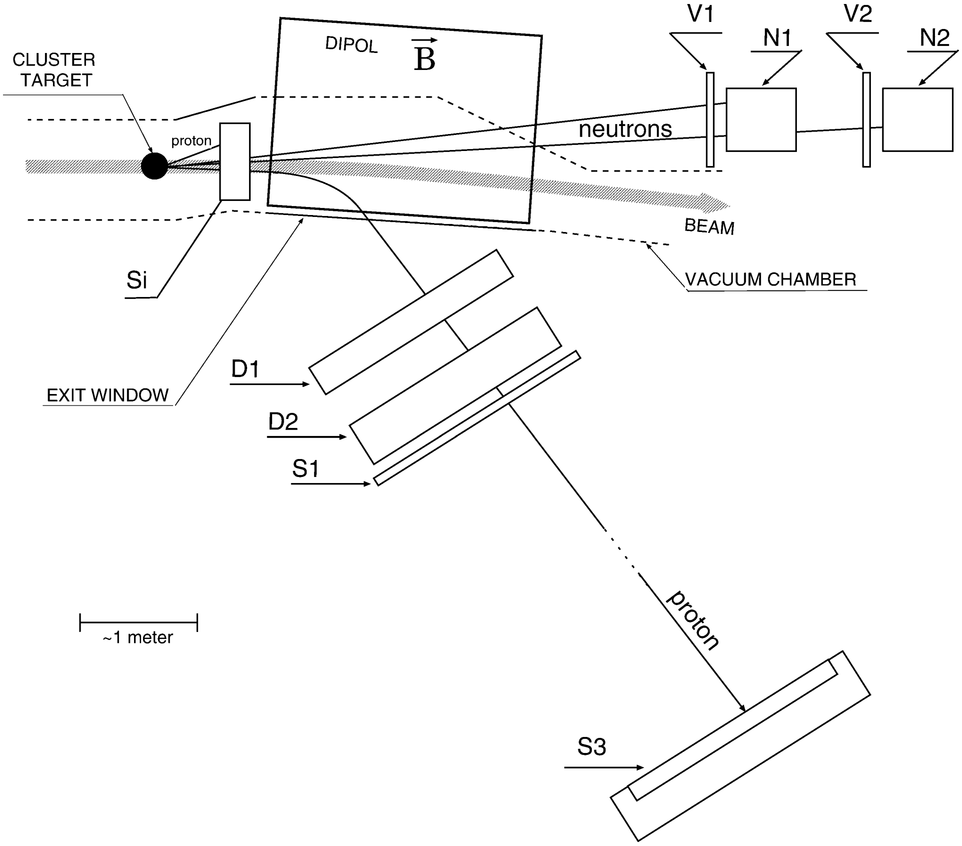

Fig. 2. Schematic view of the extended COSY-11 detection setup [35]. Only detectors needed for the measurements of the $dd \to nnp_{sp}p_{sp}X$ reactions are shown. D1, D2 denote the drift chambers used for the track reconstruction of the fast spectator proton; S1, S3 and V1, V2 are the scintillation detectors used as time-of-flight and veto counters, respectively, N1, N2 the neutron detectors, and Si [32] the silicon strip detectors.

mass resolution [34] with a calorimeter segmented by 10 cm $\times$10 cm and providing a 0.5 ns (σ) time resolution, which was obtained in test runs using a scintillator/lead sandwich type of detector.

The suggested meson production via a double quasi-free neutron–neutron reaction with precisions achievable for the proton–proton and proton–neutron reactions, opens the possibility of studying, for example, the charge symmetry breaking by comparing cross sections for the $pp \to pp\eta$ and $nn \to nn\eta$ reactions, similarly to investigations performed via the π-deuteron reactions [36]. The Dalitz-plot analysis of the $nn \to nn$ meson would allow for the study of the neutron–neutron and neutron–meson [37] scattering lengths, the first being still not well established [38] and the second being unknown. In principle when studying the meson production in proton–proton and in proton–neutron collisions one has access to all possible isospin combinations, which can be derived after the correction for the electromagnetic interaction. Exceptionally, close-to-threshold meson production via the neutron–neutron scattering represents a pure $T = 1$ isospin channel without accompanying Coulomb interaction and consequently no need for its correction. Investigations of neutron–neutron scattering allow also for the production of K^+K^- pairs in a system with only two charged particles in the final state ($nn \to nnK^+K^-$), simplifying the theoretical calculations drastically, which in case of the $pp \to ppK^+K^-$ are not feasible due to the difficulty of treating the electromagnetic forces in the system of four charged particles [39].

At present the COSY synchrotron can accelerate deuterons up to 3.5 GeV/c [40] which, utilizing the Fermi momentum, allows for the π and η meson production in the $nn \to nnX^0$ reaction. To investigate the neutron–neutron interaction with the production of heavier mesons like ω, η', or ϕ, a deuteron beam of ~ 7 GeV/c would be required.

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